# STARS OF EXTRAGALACTIC ORIGIN IN THE SOLAR NEIGHBORHOOD

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**Abstract**

We computed the spatial velocities and the galactic orbital elements using Hipparcos data for 77 nearest main-sequence F–G stars with published the iron, magnesium, and europium abundances determined from high dispersion spectra and with the ages estimated from theoretical isochrones. A comparison with the orbital elements of the globular clusters that are known was accreted by our Galaxy in the past reveals stars of extragalactic origin. We show that the relative elemental abundance ratios of r- and $\alpha$-elements in all the accreted stars differ sharply from those in the stars that are genetically associated with the Galaxy. According to current theoretical models, europium is produced mainly in low-mass Type II supernovae (SNe II), while magnesium is synthesized in larger amounts in high-mass SN II progenitors. Since all the old accreted stars of our sample exhibit a significant Eu overabundance relative to Mg, we conclude that the maximum masses of the SN II progenitors outside the Galaxy were much lower than those inside it are. On the other hand, only a small number of young accreted stars exhibit low negative ratios $[Eu/Mg] < 0$. The delay of primordial star formation burst and the explosions of high-mass SNe II in a relatively small part of extragalactic space can explain this situation. We provide evidence that the interstellar medium was weakly mixed at the early evolutionary stages of the Galaxy formed from a single proto-galactic cloud and that the maximum mass of the SN II progenitors increased in it with time simultaneously with the increase in mean metallicity.

**Keywords:** chemical composition of stars, subsystem of the Galaxy, accreted stars.

## Introduction

In recently ears, observational astronomy has provided compelling evidence that not all of the stars that currently belong to our Galaxy were formed from a single proto-galactic cloud. The Galaxy captured some of the stellar objects at different times from the nearest satellite galaxies. The epoch of accretion of isolated individual fragments and extragalactic objects probably begans at the earliest formation stages of the Galaxy and is still going on. In particular, we are currently observing the disruption of a dwarf spheroidal galaxy in Sagittarius (dSph Sgr) by tidal forces from the Galaxy (Ibata et al. 1994; Mateo 1996). Four globular clusters are confidently associated with this galaxy: M 54, Arp 2, Ter 8, and Ter 7. The cluster Pal 12 is far from this galaxy , but, according to the accurately reconstructed orbits of the two stellar systems, it was expelled from Sgr about one and a half billion ears ago (Dinescu et al. 2000). The massive globular cluster M 54 is generally believed to be the nucleus of the system (Larson 1996). In addition, it is highly likely that five more globular clusters belong to the Sgr system: M 53, Pal 5, NGC 4147, NGC 5053, and NGC 5634 (Dinescu et al. 2000; Palma and Majewski 2002; Bellazini and Ferraro 2003). The galactic orbital elements of the clusters Rup 106, Pal 13, NGC 5466, NGC 6934, and NGC 7006 also suggest that they were captured from various satellite galaxies (Dinescu et al. 2000, 2001). Freeman (1993) assumed that even $\omega$ Cen, the largest known globular cluster in the Galaxy, which is close to the Galactic centre and has a retrograde orbit, was the nucleus of a dwarf galaxy in the past. Tsuchiya et al. (2003) showed, through numerical simulations, that the disruption of a dwarf satellite by tidal forces from the Galaxy and the emergence of its central cluster in the Galaxy in a highly eccentric orbit are quite possible. All the globular clusters whose extragalactic origin has been established solely from their spatial positions and velocities exhibit redder horizontal branches than do most of the Galactic clusters with a similar metallicity. If we assume, as it was previously done by Borkova and Marsakov (2000), that all of the low-metallicity globular clusters with anomalous morphology of their horizontal branches are extragalactic in origin, then there will be a factor of $\approx 1.5$ more such clusters than low-metallicity clusters in the proto-disk halo, i.e., those formed from a single proto-galactic cloud. Therefore, accreted stellar objects constitute the bulk of the Galactic halo.

The theory of dynamical evolution predicts the inevitable dissipation of clusters through the combined actions of two-body relaxation, tidal destruction, and collisional interactions with the Galactic disk and bulge (see, e.g., Gnedin and Ostriker 1997). Indeed, traces of the tidal interaction with the Galaxy in the shape of extended deformations (tidal tails) have been found in all the clusters for which high-quality optical images were obtained (Leon et al. 2000). The latter authors even established for $\omega$ Cen that, after the last passage through the plane of the disk, this cluster lost slightly less than one percent of its mass in the form of stars. Thus, even in the nearest solar neighbourhood, we may attempt to identify stars of extragalactic origin and to find possible differences in the abundances of heavy elements between them and the stars genetically

associated with the entire Galaxy.

All the chemical elements heavier than boron are currently believed to have been synthesised in stars of various masses. According to the scenario suggested by Tinsley (1979), the presently observed lowest metallicity stars were formed from an interstellar medium enriched with the elements ejected by high mass ($M > 10M_{\odot}$) asymptotic giant branch (AGB) stars and with the elements produced during their subsequent explosions as Type II supernovae (SNe II). The characteristic explosion time of SNe II after their formation is about 30 Myr. These events inject $\alpha$- and r-elements and a few iron-peak elements. However, the production of the bulk of the iron began about one billion years after a burst of star formation, when stars with masses of $6-10M_{\odot}$ that were members of close binaries evolved and exploded as SNe Ia. The onset of the SN Ia explosion phase roughly coincides with the onset of the formation of a thick-disk subsystem. Since the contribution of SNe Ia to the synthesis of iron-peak elements is larger than their contribution to the synthesis of $\alpha$-elements, the ratio $[\alpha/Fe] \approx 0.4$, which is characteristic of low-metallicity stars, decreases to zero when going from $[Fe/H] \approx -1.0$ (the lowest metallicity thick-disk stars) to solar metallicity stars (Edvardsson et al. 1993; Fuhrmann 1998). The abundance of europium, an element produced in the r-process, behaves similarly: the value of $[Eu/Fe] \approx 0.5$ typical of lowmetallicity stars decreases with increasing metallicity, starting from $[Fe/H] \approx -1$. Both processes take place in stars whose final evolutionary stage is a SN II explosion, but the predominant yield of elements in different processes depends on the stellar mass.

Recent studies have revealed field stars that do not follow this scenario of enrichment with $\alpha$- and r-elements. Thus, in particular, Carney et al. (1997), King (1997), and Hanson et al. (1998) discovered low metallicity stars with an $[\alpha/Fe]$ ratio much smaller than its expected value. Likewise, Barris et al. (2000), Mashonkina (2000, 2003), and Mashonkina et al. (2003) found halo stars with anomalous abundances of r-elements. In other words, there is a significant spread in relative elemental abundances of the two processes among stars with $[Fe/H] < -1.0$. The nature of this spread has not yet been completely established, because various scenarios for the enrichment of the interstellar medium with chemical elements can be realised both in isolated proto-galactic fragments inside a single proto-galactic cloud and in independent satellite galaxies. Here, we make an attempt to solve this question by analysing a sample of 77 nearby stars for which reliable stellar parameters (including the abundances of certain chemical elements, ages, etc.) and their galactic orbital elements have been determined from high quality observational data.

## Observational data and stellar parameters.

We took the initial sample from the doctoral dissertation by Mashonkina (2003). It includes 77 nearby main-sequence F–G stars (we excluded one star, because no radial velocity was available for it). Most of them (66 stars) were selected from the lists by Fuhrmann (1998, 2003). Eleven more stars with $[Fe/H] < -1.0$

were specially studied by Mashonkina to extend the list toward halo stars. Since the lifetime of the stars in this spectral range on the main sequence is several billion ears, there are also the oldest stars of the Galaxy among them. In all cases, it was used spectra with a high spectral resolution (up to $\lambda/\Delta\lambda \approx 60000$) and a high signal-to-noise ratio (up to $S/N \approx 200$). Each star was observed at least twice.

All the fundamental physical parameters of the stars (Teff, log g, [Fe/H], etc.) were determined from the same observational data. The effective temperatures were estimated from Balmer line profiles with an error of $\epsilon T_{eff} \pm 80$ K. The gravitation that were determined by analysing the profiles of strong magnesium lines were almost equal to those determined from Hipparcos trigonometric parallaxes, and the error was $\epsilon \log \mathrm{g} = \pm 0.1$. The sample includes sonly stars with $\log \mathrm{g} \geq 3.5$. The value of [Fe/H] was determined with an error of $\pm 0.10$ dex. The accuracy of the above parameters strongly affects the abundance estimates for various elements. The uncertainty in the [Mg/Fe] ratio (the surrogate of $[\alpha/Fe]$) is $\pm 0.10$ dex. Mashonkina determined the relative nonLTE abundances [Eu/Fe] (the representative of r-process elements) with an error of $\pm 0.10$ dex. Bernkoff et al. (2001) estimated the ages of the stars from the isochrones by Van den Berg (1992) and Van den Berg et al. (2000) by taking into account the peculiar heavy element abundances in each star. For several thick-disk subgiants, the age was determined with an accuracy of about $\pm 1$ Gyr. Since the uncertainty in the ages of mainsequence stars can reach 2 or 3 Gyr, the individual age estimates for these stars should be treated with caution and should be used only in the statistical sense.

For all the sample stars, we calculated the distances and spatial velocity components by using the Hipparcos catalogue and the radial velocity catalogue Barbier-Brossat and Figon (2000). The galactic orbital elements were calculated by using a multi-component model of the Galaxy that consisted of a disk, a bulge, and an extended massive halo (Allen and Santillan 1991). We assumed that the galactocentric distance of the Sun was 8.5 kpc, the Galactic rotation velocity at the solar galactocentric distance was 220km s$^{-1}$, and the velocity of the Sun with respect to the local standard of rest was $(U_{\odot}, V_{\odot}, W_{\odot})$= (-10, 10, 6)km s$^{-1}$. A list of stars with all the parameters calculated and used here is given in the table.

Despite the small size of our sample, it contains representatives of all Galactic subsystems (except the bulge). Its representativeness is slightly violated by the fact that the low metallicity stars were chosen from a larger volume of space to compensate for their scarcity in the solar neighbourhood, which is attributable to the high velocities of these stars (particularly their W component). However, even a few stars with $[Fe/H] < -1.0$ (22 stars) can reveal some of the global patterns of their behaviour because of the high accuracy of the parameters obtained for them.

## Criteria for separating thin and thick disk stars

While analysing the properties of F–G dwarfs from his sample, Fuhrmann (1998) found that the Mg abundance relative to iron increased abruptly when going from the thin disk to the thick disk. This author clearly showed that there was a gap in ages of about 2 or 3 Gyr between these subsystems. Marsakov and Suchkov (1977) first pointed out the existence of a delay in star formation in the Galaxy prior to the formation of the Galactic thin-disk subsystem. Since the thin-disk stars are known to have low peculiar velocities relative to the local standard of rest ($V_{pec}$), we separated this subsystem by using two criteria: $t \leq 9\,\mathrm{Gyr}$ and $V_{pec} \leq 100 \mathrm{km\,s^{-1}}$. A comparison of Figs. 1a and 1b indicate that these two criteria automatically separate stars with $[Mg/Fe] \leq 0.25$ (except one thick disk star that fell within this range). In the [Fe/H]–[Mg/Fe] diagram, we clearly see a gap of $\Delta[Mg/Fe] \approx 0.1$ between the stars of the two disk subsystems. However, we also simultaneously see a mutual overlapping of the ranges both in metallicity and in peculiar velocities (and, hence, in orbital sizes). In other words, [Fe/H] and $V_{pec}$ here are less suitable criteria for the individual separation of stars of these subsystems from one another.

Objectively, thick disk stars are much more difficult to separate from protodisk halo stars genetically associated with them. The ages of most of the stars that do not belong to the thin disk lie within a narrow time interval and we can say nothing about the difference between the formation epochs of these subsystems because of the errors in its determination. However, based on an abundance analysis, Mashonkina et al. (2003) concluded that, although the time intervals of these subsystems overlap, star formation in the thick disk began about 1 Gyr later than in the halo. The subsystems can be separated in $[Fe/H] \approx -1.0$. Indeed, the metallicity distributions for globular clusters near this point exhibit a large deficit of stars (Borkova and Marsakov 2000), while the RR Lyrae field stars show a distinct inflection (Borkova and Marsakov 2002). In this case, however, a number of stars with circular orbits, which are characteristic of the disk subsystem, fall into the halo. Here, we decided to use the peculiar velocity as the criterion. If we separate the sample stars by $V_{pec} \approx 155 \mathrm{km\,s^{-1}}$, then only one star with $[Fe/H] > -1.0$ will be in the halo, and two low metallicity stars will be in the thick disk. Such stars in the thick disk are commonly called a low metallicity tail.

## The protodisk and accreted halo subsystems

There is no unique necessary and sufficient statistical criterion that would separate extragalactic objects. In each specific case, all the available parameters should be considered simultaneously. To stratify the field stars into the halo subsystems, different authors primarily used such parameters as the retrogradation of their orbits and their distances from the Galactic centre and plane. Naturally, the thick disk objects must first be removed from the sample (see above). The galactic orbital elements of the stars, their ages, and the abun-

dances of $\alpha$-elements in them have been most commonly used as additional criteria (for an overview of the criteria, see the monograph by Carney 1999). For globular clusters, the morphology of their horizontal branches proved to be a good criterion (see, e.g., Borkova and Marsakov 2000). Thus, it has been shown that the objects that constitute the accreted halo have apogalactic orbital radii larger than the galactocentric distance of the Sun, high orbital eccentricities, high velocity dispersions, low-rotation velocities (many of them are in retrograde orbits), often younger ages, and an underabundance of $\alpha$-elements. The vertical and radial metallicity gradients are virtually equal to zero in the resulting subsystem. Studies of RRLyrae variables (Borkova and Marsakov 2002, 2003) show that a convenient criterion for field stars in the solar neighbourhood is the total peculiar velocity of the star relative to the local standard of rest ($V_{pec}$): when passing through some critical peculiar velocity (which is definitely higher than the circular velocity of Galactic rotation at the solar galactocentric distance), the spatial kinematics characteristics of the stars change abruptly. These changes suggest that all the low metallicity population of field RR Lyrae variables is not homogeneous, but consists of at least two subsystems that differ in the volume occupied in the Galaxy (Borkova and Marsakov 2002, 2003). The most compelling argument for the extragalactic origin of a specific star is probably a close match between its orbital elements and chemical composition and the analogous parameters of the globular cluster for which it has been firmly established that it was accreted by our Galaxy in the past.

According to the hypothesis of monotonic collapse of the proto- galaxy from the halo to the disk suggested by Eggen et al. (1962), the stars that are genetically associated with the Galaxy cannot be in retrograde orbits. On the other hand, there must also be stars with prograde orbits among the stars accreted by the Galaxy. In any case, the velocity of the accreted stars with respect to the local standard of rest must be very high. Therefore, the most natural criterion for separating accreted halo stars seems to be the peculiar velocity. It follows from the $V_{pec} - \Theta$ diagram in Fig. 1c that stars with a negative tangential velocity, i.e., in retrograde orbits, appear when passing through $V_{pec} \geq 250 \mathrm{km\,s}^{-1}$. The $V - \sqrt{U^2 + W^2}$ diagram (see Fig. 1d) shows how the objects of the separated subsystems are distributed in the plane of the peculiar velocity components. Within the thin and thick disks, the total peculiar velocity increases mainly through a decrease in the rotation velocities of the stars around the Galactic centre. At the same time, when going to the halo subsystems, the contributions from the other two velocity components increase sharply. Note the very small number of stars in the proto-disk halo compared to the number of stars that are assumed to have been captured from extragalactic space. As we pointed out above, observational selection is certain to have played a role here: mostly highvelocity stars were selected for the initial sample of low metallicity stars. Recall, however, that globular clusters also exhibit a similar ratio of the numbers, although the accreted halo objects were selected thereby their internal property, the structure of the horizontal branch, rather than by their spatial position (Borkova and Marsakov 2000).

Let us consider the properties of the stars that we selected as accretedhalo

candidates in more detail. We see from the $V_{pec} - t$ diagram (Fig. 1a) that there are very young stars among them whose ages fall even within the range characteristic of the thin disk. As follows from Fig. 2 (crossed circles), the orbital elements are indicative of their obvious extragalactic origin. Four stars with prograde orbits can also raise doubts about their origin. In Fig. 2, they are highlighted by circles with a central dot. All of them have apogalactic orbital radii larger than 15 kpc; the maximum distance of three stars from the Galactic plane is larger than 3 kpc, and all stars have highly eccentric ($e > 0.8$) orbits and old ages. These orbital elements fall within the range of parameters characteristic of the globular clusters that are assumed with a high probability to be accreted ones (Borkova and Marsakov 2000). Since no globular clusters with extremely blue branches (i.e., belonging to the proto-disk halo) are observed at such large galactocentric distances, we conclude that these four high velocity stars with prograde orbits may have been lost by the accreted clusters and be extragalactic in origin.

The origin of yet another stellar group, the cluster of five stars in Fig. 1c with coordinates $V_{pec} \sim 280 \mathrm{km\,s}^{-1}$ and $\approx -30 \mathrm{km\,s}^{-1}$ (HD 148816,194598, 193901, BD -4°3208, 18°3423), can also raise doubts. Small circles inside large circles in Fig. 2 highlight them. It may well be that at the early evolutionary stages of the proto-galaxy, some of the giant clouds could accidentally acquire a small negative rotation around the Galactic centre through their natural velocity dispersion. In that case, these stars must be oldest, their chemical composition must correspond to the composition of the first Galactic stars, and the maximum distances of the points of their orbits from the Galactic centre and plane must be large. Their orbital eccentricities turned out to be actually very high ($e \leq 0.9$). However, their apogalactic radii are very small, the orbits for four of the five stars completely lie within the solar circle, and their ages lie within a wide range, so three of the five stars are younger than 12 Gyr (see Fig. 2). These properties are in conflict with the hypothesis that all these stars originated from a single proto-galactic cloud. Note that the orbital elements of the stars from the group under discussion are satisfactory agreement with those of the largest globular cluster $\omega$ Cen, which, as was pointed out above, is probably extragalactic in origin.

Note also the star HD 298986, whose orbital elements are equal, within the error limits, to the corresponding parameters of the accreted globular cluster Pal 5 (which probably belonged to dSph Sgr). According to the model of the Galaxy by Allen and Santillan (1991) used here, the parameters for the stars and the clusters were found to be the following. Apogalactic orbital radii of 22 and 19 kpc, perigalactic radii of 2 and 1.5 kpc, and $Z_{max} = 13$ and 17 kpc, respectively. A comparison also indicates that the star and the cluster have not only similar $[Fe/H]$ ($-1.34$ and $-1.41$ dex) and $[\alpha/Fe]$ (about 0.16 dex each), but also similar ages (about 13 Gyr each).

In the next section, we show that all of the stars attributed to the accreted halo by their kinematics exhibit sharp chemical anomalies.

## The chemical composition of accreted halo stars

The $\alpha$- and r-elements are generally believed to be synthesised in stars with masses $M > 10M_{\odot}$ and injected into the interstellar medium by SN II explosions. Therefore, the most probable [Eu/Mg] ratio for the Galactic stars must be equal to zero. However, the yield of $\alpha$-elements increases with mass of the SN II progenitor; the amount of magnesium increases by a factor of 10 to 20 $M\odot$ as the mass of the SN progenitor changes from 13 to 25 (Thielemann et al. 1996). On the other hand, the yield of relements is related to the explosions of the lowest mass type II super novae (see, e.g., Wheeler et al. 1998, Ishimaru et al. 2004). Mashonkina et al. (2003) performed a comparative analyis of the relative abundances of magnesium (an a-element) and europium (an r-element). They found that the halo stars exhibit a significant spread in Eu abundances relative to Mg, while the thin disk and thick disk stars have $[Eu/Mg] \approx 0$ with a smaller spread (the Galaxy was assumed to consistently of three subsystems only.) These authors also considered all the possible causes of this abundance anomaly in the halo stars and concluded that the bulk of the Galactic europium and magnesium were produced in stars of different masses, and that the interstellar medium was weakly mixed in the early Galaxy. Figure 3 shows a [Fe/H]–[Eu/Mg] diagram for the same sample, but the stars were stratified into four Galactic subsystems. We see from the figure that all the accreted halo stars exhibit deviations from the most probable zero [Eu/Mg] ratio, while among the remaining stars, only two proto-disk halo stars (HD 25329 and HD 102200) exhibit such deviations.

We believe that the large spread in [Mg/Fe] is an argument for inefficient mixing of the interstellar medium in the halo. However, it follows from the [Fe/H]–[Mg/Fe] diagram (see Fig. 1b) that this spread is most likely associated with the accreted halo. Six of the seven proto-disk halo stars from our list have relative Mg abundances that lie within a narrow range, $0.32 - 0.47$ dex (except the star HD 122196 with an anomalously low ratio, $[Mg/Fe] = 0.16$). Whereas the accreted halo stars occupy the range from 0.12 to 0.51 dex, half of them (9 of the 16 stars) have Mg abundances $< 0.3$ dex. In other words, the stars formed far from the Galactic centre exhibit relative heavy element abundances that often differ from those in the stars formed inside the proto-galactic cloud. Clearly, not in all of the tidally disrupted dwarf galaxies, the star formation history must be the same as that in our Galaxy. Because of the large number of disrupted galaxies and globular clusters as well as the large stellar dispersion within the tidal tails from them, the stars that were formed from proto-stellar clouds with different histories of enrichment with chemical elements will most likely be in the solar neighbourhood.

As was pointed out above, the accuracy of determining the ages for low mass main sequence stars is too low to obtain their statistically significant differences. Nevertheless, we formally divided all the accreted halo stars into two age groups. At the same time, the difference between the mean ages of these stars exceeds the error limits ($\triangle t \approx 4 \pm 1$ Gyr). Therefore, let us consider the chemical composition of the stars in each age group. In Figs. 1b and 3, the open crossed circles highlight the accreted halo stars younger than $t < 12.5$ Gyr. For approximately

the same Mg abundance as that for protodisk-halo and thick disk stars, four of the highlighted young stars (except HD 193901) exhibit an Eu underabundance relative to Mg. (In the star BD -4°3208 with a high ratio of $[Mg/Fe] = 0.34$, the Eu abundance has not been determined, probably because the line of this element is too weak; therefore, we attributed it to the group with a low [Eu/Mg] ratio.) Mashonkina et al. (2003) excluded two stars with an Eu underabundance (HD 34328 and HD 74000)by concluding that they "did not reflect the overall pattern of chemical evolution of the matter in our Galaxy". We believe that the very young low metallicity stars with $[Eu/Mg] < 0$ were formed from matter that was mainly enriched by high mass ($M > 30M_{\odot}$) SNe II. According to existing theories for the formation of chemical elements, the low metallicity of these stars at a high $[Mg/Fe]$ ratio suggests that they are old. Thus, the ages estimated from evolutionary tracks are in conflict with their "chemical" ages. If the "isochronic" ages are actually accurate enough, then this contradiction can be resolved by assuming that the low metallicity for the anomalously young age of these stars is attributable to their formation from matter in which the primordial starburst occurred later than that in the single proto-galactic cloud. Naturally, this assumption should be further tested on large statistical material. The increasingly old accreted halo stars in Fig. 3 exhibit a significant overabundance, $[Eu/Mg] > 0.2$, with the Mg abundance relative to Fe being lower than that observed, on average, for the proto-disk halo and thick disk stars: it follows from Fig. 1b that six of the seven protodiskhalo stars have $[Mg/Fe] > 0.3$, while this ratio for eight of the eleven old ($t > 12.5$ Gyr) accreted halo stars is $< 0.3$. The europium overabundance relative to magnesium in most of the old accreted halo stars suggests that the initial mass function of the stars formed outside the proto-galaxy was cut-off at high masses and began from. As a result, the yield of $\alpha$-elements was smaller than that within the single proto-galactic cloud, where the masses of the SN progenitors were larger by several times. This interpretation also accounts for the low Mg abundance relative to iron in old accreted stars (see Fig. 1b). Indeed, the low $[\alpha/Fe]$ ratio for very old low metallicity stars can be more naturally explained by the low masses of the SN II progenitors than by the injection of iron-group elements by SNe Ia, because an Eu underabundance must then be also simultaneously observed in these stars. However, as we see, europium is overabundant in these stars. Van den Berg (2000) explained the low oxygen abundance in the stars of the very old low metallicity globular cluster M 54, which is the centre of the dwarf galaxy Sgr, precisely by the deficit of highmass SN II progenitors. It thus follows that the low abundance of $\alpha$-elements alone in stars cannot unambiguously point to slow star formation in their parent proto-stellar cloud, as was suggested by Gilmore and Wyse (1998). This quantity is often taken as a "chemical" indicator of a young stellar age (see, e.g., Carney et al. 1997; King 1997; Hanson et al. 1998). Figure 1b also clearly shows that old stars with even lower relative Mg abundances appear near $[Fe/H] \approx -1.3$ dex. Whereas nine of the eleven stars from the old group of accreted stars have $[Mg/Fe] > 0.24$ dex, the stars HD 298986 and BD 18°3423, being in the range $-1.3 \leq [Fe/H] \leq -0.9$ dex, exhibit $[Mg/Fe] \approx 0.15$ dex (i.e., there is a difference exceeding the error limits).

Although the "isochronic" ages of the two stars are within the error limits, they are still about one billion years younger than the oldest stars of extragalactic origin; i.e., a time long enough for SN I explosions to occur had elapsed by the time of their formation. HD 193901, which we included in the young group of accreted stars, lies in the same place in the diagram. This behaviour can be understood by assuming that the intergalactic matter from which all the accreted stars in the old group were formed acquired the primordial injection of heavy elements simultaneously with the proto-Galaxy , but from SNe II with masses much lower than those of the SNe exploded inside the proto-Galaxy itself. Subsequently, the star formation there was so slow that SNe Ia began to contribute appreciably to the iron abundance even at $[Fe/H] \approx -1.3$.

Note the two properties that the genetically associated stars exhibit in Fig. 3. First, there is a spread in $[Eu/Mg]$ in the proto-disk halo: one of the stars that we attributed to this subsystem exhibits a large Eu abundance at a low Mg abundance (HD 102200), while another star exhibits a low Eu abundance at a high Mg abundance (HD 25329). Weak mixing of the interstellar medium appears to have actually taken place at the early evolutionary stages of our Galaxy, and stars were formed from clouds enriched by ejections from SNe II with different masses in its different places. Note also that all the remaining genetically associated stars show a tendency for $[Eu/Mg]$ to decrease with increasing [Fe/H] at a relatively small spread (the correlation coefficient outside the $3\sigma$ limits is nonzero, $r = 0.4 \pm 0.1$). This behaviour suggests that the maximum mass of the SN II progenitors formed inside the Galaxy increases with metallicity. The observed trend is also obtained if some amount of Mg is assumed to be additionally formed in AGB stars with, but none of the existing theories for the synthesis of heavy elements makes this assumption. Here, however, it should be borne in mind that a systematic bias of the Mg and Eu abundance estimates as a function of metallicity can arise, because the abundances of these elements are determined from lines of different ionisation stages, Mg I and Eu II.

# Discussion

Thus, the galactic orbital elements and the ($\alpha$- and r-process) elemental abundances in the stars of the nearest solar neighbourhood strongly suggest that some of them may be extragalactic in origin. The detected overabundance $< [Eu/Mg] >= 0.30 \pm 0.03$ in all the old accreted stars of our sample (see Fig. 3) can be explained only by assuming that the initial mass function of the stars being born outside the Galaxy is cut-off at high masses. The simple assumption about weak mixing of the intergalactic matter with a single initial mass function for the entire local system seems to be less tenable. Indeed, the natural isolation of the explosion sites of SNe II with different masses from one another must give rise to the next generations of stars, with an overabundance of both europium and magnesium. Moreover, since they yield of $\alpha$-elements becomes well ahead of the yield of r-elements as the mass of the SN II progenitor increases, we must detect Mg-over-abundant stars with a higher probability than Eu-over-abundant

stars. However, interference from observational selection is possible here: the Eu lines used to estimate the Eu abundance in a star will be so weak that they will be lost in spectral noise. Thus, the Eu abundance cannot be determined in a star where the amount of this element is small. As a result, a deficit of stars with $[Eu/Mg] < 0$ can arise in the sample. In our sample, we attributed 16 stars to the accreted halo. Eight and three of these stars exhibit $[Eu/Mg] > 0.2$ and less than zero, respectively. For five stars, the Eu abundance has not been determined. The metallicity of all five stars is approximately two orders of magnitude lower than its solar value. For two of them, $[Mg/Fe] < 0.3$ dex, while for the other three stars, the Mg abundance is comparable to its abundance in the protodisk-halo and thick-disk stars. We may assume a relative Eu underabundance in the last three stars and an Eu overabundance in the first two stars. Thus, we have ten stars with an Eu underabundance and six stars with an Eu overabundance relative to Mg; i.e., only about a third of the stars could be formed from matter enriched by the explosions of highmass SNe II. Four of the above six stars with $[Eu/Mg] < 0$ are younger than 12.5 Gyr (BD -4°3208, HD 74000, HD 34328, and HD 148816); above, we have assumed a later initial burst of star formation in the part of the extragalactic interstellar medium from which they were formed. Hence, high-mass SN progenitors began to explode in extragalactic space much later. The small number of accreted stars with an Eu underabundance in our sample most likely implies that high mass SN progenitors outside the Galaxy do not determine the situation. However, for a Salpeter mass distribution of stars, SN progenitors with $M > 30M_{\odot}$ (they are believed to be the main suppliers of magnesium) must contaminate a much larger volume of the interstellar medium with $\alpha$-elements than the volume that SNe II with masses of $\approx 10M_{\odot}$ (the main suppliers of europium) contaminate with r-elements. This is because the yield of $\alpha$elements in high-mass SN progenitors is a factor of about 20 larger than that in low mass SN progenitors (Thielemann et al. 1977), while they yield of r-elements decreases (Wheeler et al. 1998). Thus, we believe that weak mixing of the extragalactic medium can explain only the general spread in $[Eu/Mg]$ ratios in the accreted halo, while the dominance of stars with an Eu overabundance relative to Mg in it is probably attributable to the lower masses of the SN II progenitors outside Galaxy than those in the Galaxy.

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# References

[1.] Allen, C., &. Santillan, A. 1991, Rev. Mex. A&A, 22, 255

[2.] Barbier-Brossat, M. and Figon, P. 2000, A&AS, 142, 217

[3.] Barris, D.L., Pilachowski, C.A., Armandroff, T.E.,et al., 2000, ApJ, 544, 302

[4.] Bellazini, M. and Ferraro, F.R., 2003, AJ, 125, 188

[5.] Bernkoff, J., Fiedler, A., and Fuhrmann, K., 2001, ASP Conf. Ser. 245, p. 207

[6.] Borkova, T. V., & Marsakov, V. A. 2000, Astron. Rep., 44, 665

[7.] Borkova, T. V., & Marsakov, V. A., 2002, Astron. Rep. 46, 460

[8.] Borkova, T. V., & Marsakov, V. A., 2003, A&A, 398, 133

[9] Carney, B.W., 1999, Globular Clusters (Univ. Chapel Hill, USA,).

[10.] Carney, B.W., Wrigen, J.S., Sneden, C., et al., 1997, AJ, 114, 363

[11.] Dinescu, D., Majewski, S.R., Girard, T.M., and Cudworth, K.M., 2000, AJ, 120, 1892

[12.] Dinescu, D., Majewski, S.R., Girard, T.M., and Cudworth, K.M., 2001, AJ, 122, 1916

[13.] Gnedin, O.Yu. and Ostriker, J.P., 1997, ApJ, 474, 223

[14.] Edvardsson, B., Andersen, J., Gustafsson, B., et al., 1993, A&A, 275, 101

[15.] Eggen, O.J., LindenBell, D., and Sandage, A.R., 1962, ApJ, 136, 748

[16.] Freeman, K., 1993, IAU Symp. N?153: Galactic Bulges, Eds. by H. Dejonghe and H. J. Hobiug (Kluwer, Dordrecht), p. 263.

[17.] Fuhrmann, K., 1998, A&A, 338, 183

[18.] Fuhrmann, K., 2003, Astron. Nachr. (in press).

[19.] Gilmore, G. and Wye, R.F.G., 1998, ApJL. 367, L55

[20.] Hanson, R.B., Sneden, C., Kraft, R.P., and Fulbright, J.P., 1998, AJ, 116, 1286

[21.] Ibata, R., Gilmore, G. and Irvin, M., 1994, Nature 370, 194

[22.] Ishumaru, Y., Wanajo, S., Aoki, W. and Ruan, S., 2004, ApJL., 600, L47

[23.] King, L.R., 1997, AJ, 113, 2302

[24.] Larson, R.B., 1996, ASP Conf. Ser. 92, p. 241

[25.] Leon, S., Meylan, G., and Combes, F., 2000, A&A, 359, 907

[26.] Marsakov, V.A., & Suchkov, A.A., 1977, SvA, 21, 700

[27.] Mateo, M., 1996, ASP Conf. Ser. 92, 434

[28.] Mashonkina, L., 2000, A&A, 364, 249

[29.] Mashonkina, L.I., Doctoral Dissertation in Mathematical Physics (St. Petersburg, 2003).

[30.] Mashonkina, L., Gehren, T., Travaglio, C., and Borkova, T., 2003, A&A, 397, 275

[31.] Palma, C. and Majewski, S.R., 2002, ApJ, 564, 736

[32.] Thielemann, F.-K., Nomotto, K., and Meyned, G., 1977, ApJ, 460, 408

[33.] Tinsley, B.M., 1979, ApJ, 229, 1046

[34.] Tsuchiya, T., Dinescu, D., and Korchagin, V.I., 2003, ApJL. 589, L29

[35.] VandenBerg, D.A., 1992, ApJ, 391, 685

[36.] VandenBerg, D.A., Swenson, E.J., Rogers, F.J., et al., 2000, ApJ, 532, 430

[37.] van den Bergh, S., 2000, ApJ, 530, 777

[38.] Wheeler, J.C., Cowan,J.J., and Hillebrandt, W., 1998, ApJL. 493, L101

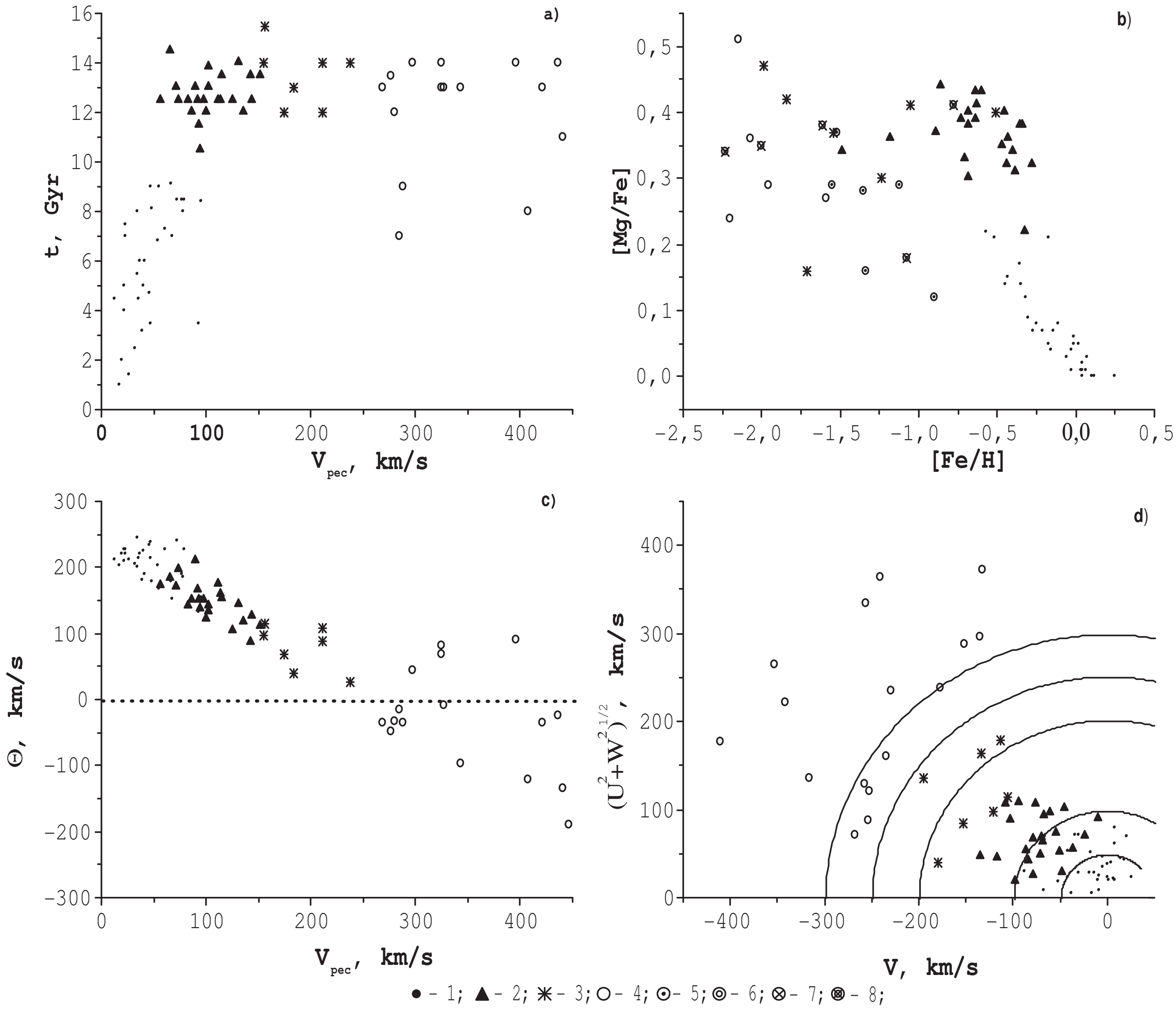


Figure 1: Correlations between the peculiar stellar velocities with respect to the local standard of rest and the stellar ages (a), between the metallicity and the relative Mg abundance (b), between the peculiar velocities and the stellar rotation velocities around the Galactic centre (c), and between the peculiar stellar velocity components: 1 – think disk stars, 2 – thick disk stars, 3 – proto-disk-halo stars, and 4 – accreted halo stars. The following stars are additionally marked in the accreted halo in panel (b): 5 – stars with prograde orbits, 6 – stars of the cluster from (c) with coordinates of $V_{pec} \approx 280\mathrm{km\,s^{-1}}$ and $\Theta \approx -30\mathrm{km\,s^{-1}}$, 7 and 8—stars younger than 12.5 Gyr

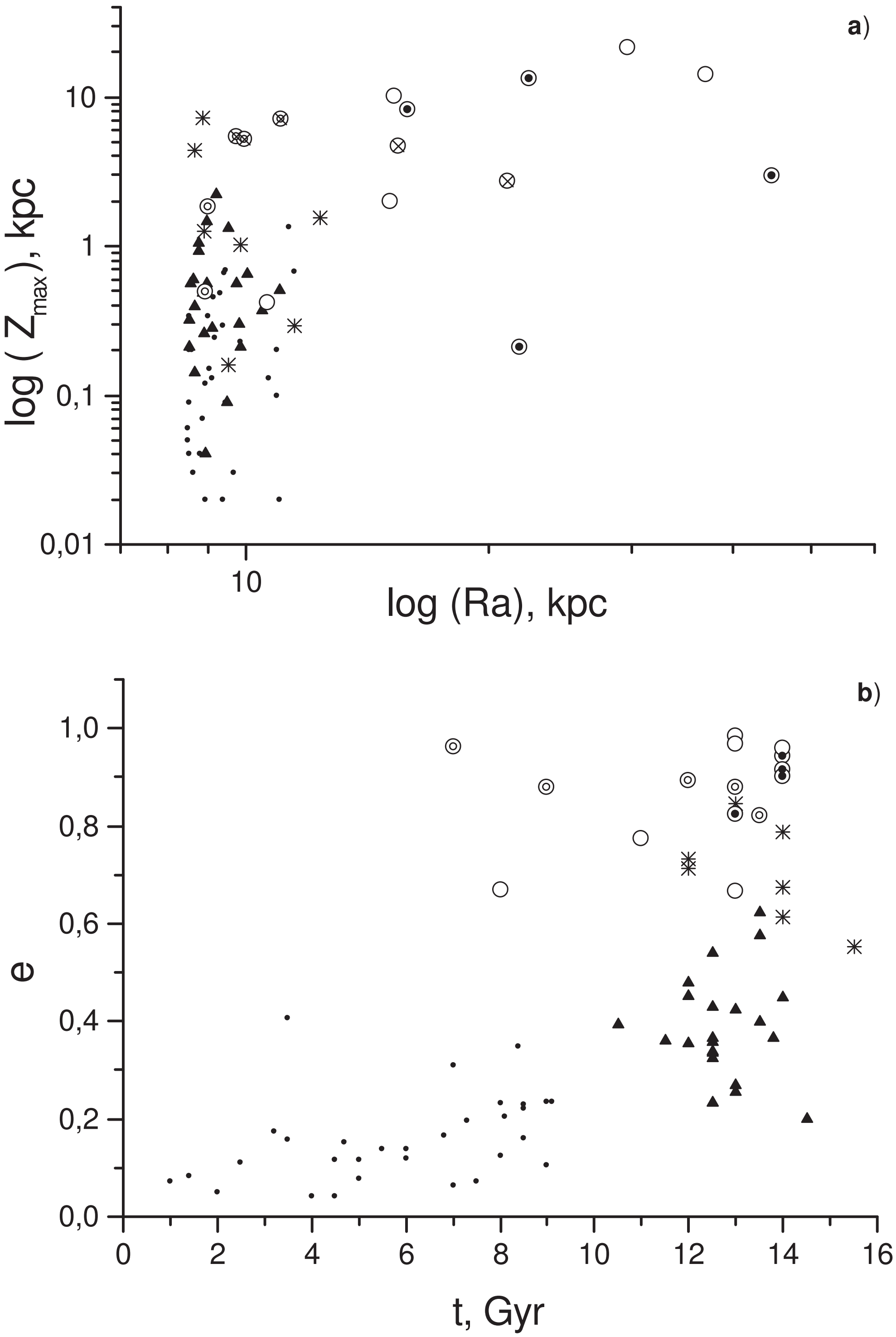


Figure 2: Correlations between the maximum distances of the points of stellar orbits from the Galactic centre and plane (a) and between the ages and the orbital eccentricities of stars (n). The notation is the same as that in Fig. 1.

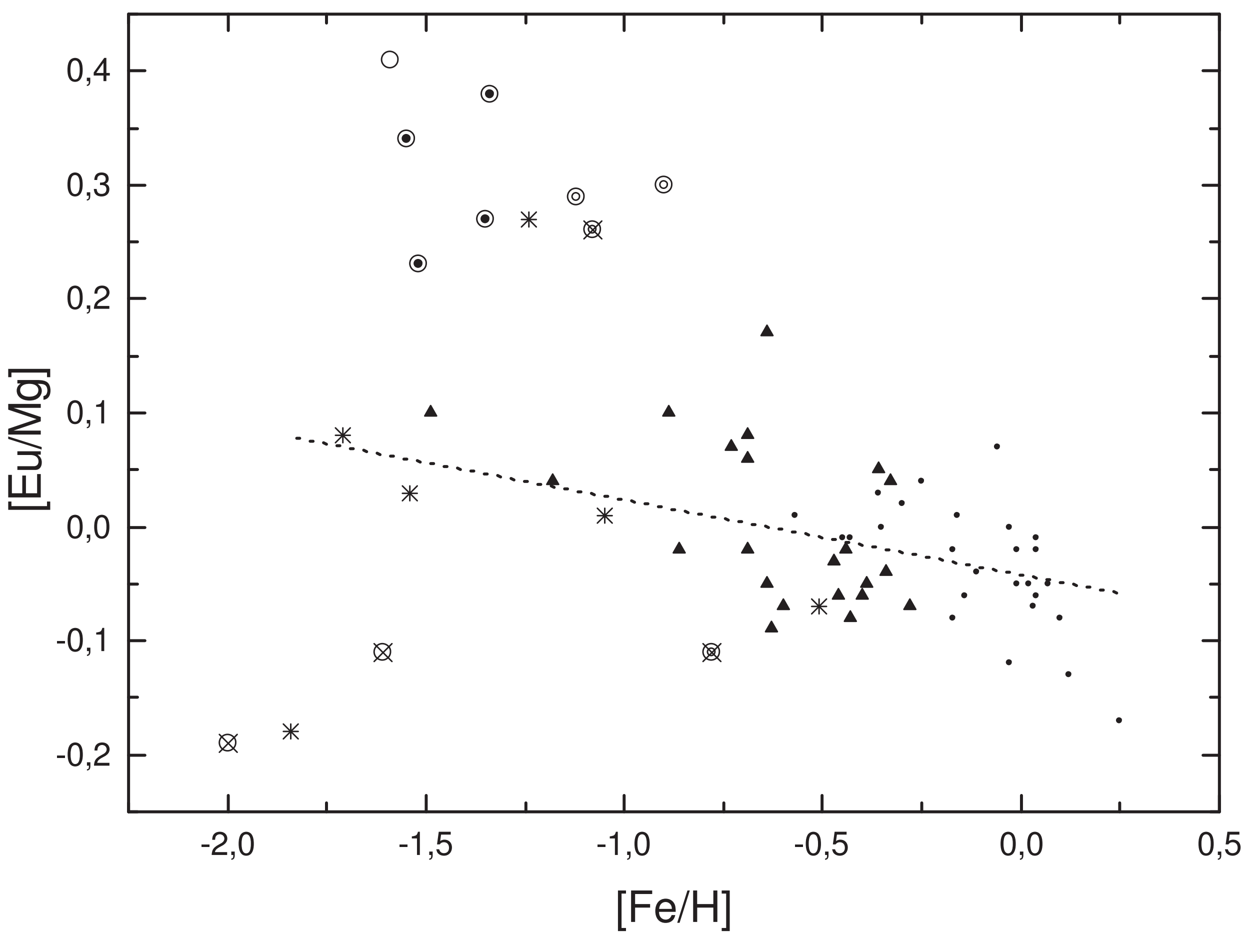


Figure 3: Correlation between the iron abundances and the $[Eu/Mg]$ ratios for stars in the solar neighbourhood. The notation is the same as that in Fig. 1. The dotted line represents an rms regression for the genetically associated stars ($r = 0.4 \pm 0.1$).

Table 1: **Chemical composition and galactic orbital elements of the nearest field stars**

| HD/BD | [Fe/H] dex | [Mg/Fe] dex | [Eu/Fe] dex | t, Gyr | U, km/s | V, km/s | W, km/s | $V_{pec}$, km/s | Ra, kpc | $Z_{max}$, kpc | e | code |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 400 | -0.25 | 0.08 | 0.12 | 6.0 | -27.2 | -9.2 | -8.4 | 37.2 | 9.7 | 0.0 | 0.12 | 1 |
| 3795 | -0.64 | 0.39 | 0.56 | 13.8 | 50.4 | -88.9 | 45.6 | 102.6 | 8.8 | 0.9 | 0.37 | 2 |
| 4614 | -0.30 | 0.09 | 0.11 | 7.0 | 29.9 | -10.0 | -16.8 | 22.6 | 9.1 | 0.1 | 0.06 | 1 |
| 9407 | 0.03 | 0.01 | -0.06 | 7.3 | -50.4 | -2.0 | 1.4 | 61.3 | 10.9 | 0.1 | 0.20 | 1 |
| 10519 | -0.64 | 0.43 | 0.38 | 13.5 | 96.5 | -77.6 | 29.3 | 115.3 | 9.8 | 0.6 | 0.40 | 2 |
| 10697 | 0.10 | 0.00 | -0.08 | 6.8 | -36.0 | -27.5 | 16.2 | 54.0 | 9.4 | 0.3 | 0.17 | 1 |
| 18757 | -0.28 | 0.32 | 0.25 | 11.5 | 68.6 | -79.2 | -27.7 | 93.3 | 9.1 | 0.3 | 0.36 | 2 |
| 19445 | -1.99 | 0.47 | | 14.0 | -157.2 | -122.0 | -67.1 | 210.8 | 12.4 | 1.6 | 0.67 | 3 |
| 22879 | -0.86 | 0.44 | 0.42 | 14.0 | 108.9 | -86.0 | -44.8 | 130.7 | 10.1 | 0.6 | 0.45 | 2 |
| 25329 | -1.84 | 0.42 | 0.24 | 13.0 | 40.2 | -189.0 | 19.9 | 183.9 | 8.6 | 4.4 | 0.85 | 3 |
| 29907 | -1.55 | 0.29 | 0.63 | 14.0 | 381.2 | -142.0 | 27.8 | 395.7 | 44.8 | 3.0 | 0.94 | 4 |
| 30649 | -0.47 | 0.35 | 0.32 | 12.0 | 58.5 | -80.6 | -9.6 | 85.7 | 8.9 | 0.0 | 0.35 | 2 |
| 30743 | -0.45 | 0.14 | 0.13 | 5.0 | -25.8 | -5.4 | -23.6 | 40.1 | 9.9 | 0.2 | 0.12 | 1 |
| 31128 | -1.49 | 0.34 | 0.44 | 13.0 | 59.4 | -97.1 | -26.1 | 102.1 | 8.9 | 0.3 | 0.42 | 2 |
| 34328 | -1.61 | 0.38 | 0.27 | 8.0 | 207.7 | -352.0 | 95.6 | 407.9 | 15.4 | 4.7 | 0.67 | 4 |
| 37124 | -0.44 | 0.32 | 0.30 | 14.5 | -28.7 | -46.5 | -43.7 | 65.2 | 9.0 | 0.6 | 0.20 | 2 |
| 43042 | 0.04 | 0.00 | -0.02 | 1.4 | 32.5 | -18.4 | -16.6 | 26.2 | 8.9 | 0.1 | 0.08 | 1 |
| 45282 | -1.52 | 0.37 | 0.60 | 14.0 | 245.8 | -186.0 | -43.7 | 297.0 | 15.9 | 8.2 | 0.91 | 4 |
| 52711 | -0.16 | 0.04 | 0.05 | 7.0 | 18.5 | -77.5 | -9.2 | 68.1 | 8.5 | 0.0 | 0.31 | 1 |
| 55575 | -0.36 | 0.17 | 0.20 | 8.5 | 79.5 | -1.8 | 32.1 | 79.7 | 11.5 | 0.7 | 0.23 | 1 |
| 58855 | -0.32 | 0.12 | | 4.5 | -25.4 | -15.1 | -4.2 | 35.8 | 9.4 | 0.0 | 0.12 | 1 |
| 59392 | -1.59 | 0.27 | 0.68 | 13.0 | -123.0 | -325.0 | -32.3 | 343.5 | 10.6 | 0.4 | 0.67 | 4 |
| 61421 | -0.01 | 0.06 | 0.01 | 2.0 | -5.4 | -8.3 | -18.8 | 20.1 | 9.0 | 0.2 | 0.05 | 1 |
| 62301 | -0.69 | 0.30 | 0.36 | 12.0 | 5.5 | -108.0 | -23.4 | 100.1 | 8.5 | 0.2 | 0.45 | 2 |
| 64606 | -0.89 | 0.37 | 0.47 | 12.5 | 82.4 | -65.2 | 1.4 | 91.3 | 9.5 | 0.1 | 0.33 | 2 |
| 65583 | -0.73 | 0.39 | 0.46 | 12.5 | 12.0 | -88.6 | -30.9 | 82.5 | 8.5 | 0.3 | 0.36 | 2 |
| 67228 | 0.12 | 0.00 | -0.13 | 4.7 | -32.8 | 4.1 | -15.9 | 46.1 | 10.7 | 0.1 | 0.15 | 1 |
| 68017 | -0.40 | 0.34 | 0.28 | 13.0 | 48.1 | -60.4 | -39.6 | 71.5 | 8.8 | 0.5 | 0.25 | 2 |
| 69611 | -0.60 | 0.43 | 0.36 | 13.5 | 38.3 | -144.0 | -43.4 | 142.4 | 8.6 | 0.6 | 0.62 | 2 |
| 74000 | -2.00 | 0.35 | 0.16 | 11.0 | -245.7 | -362.0 | 59.5 | 440.3 | 21.1 | 2.7 | 0.77 | 4 |
| 84937 | -2.07 | 0.36 | | 13.0 | -224.5 | -238.0 | -8.3 | 327.7 | 15.3 | 10.1 | 0.99 | 4 |
| 90508 | -0.33 | 0.22 | 0.26 | 10.5 | -21.0 | -94.2 | 22.4 | 94.1 | 8.7 | 0.4 | 0.39 | 2 |
| 97320 | -1.18 | 0.36 | 0.40 | 13.0 | -73.1 | -20.0 | -37.5 | 89.4 | 11.0 | 0.5 | 0.27 | 2 |
| 99383 | -1.54 | 0.37 | 0.40 | 14.0 | 23.2 | -204.0 | 129.0 | 237.1 | 8.9 | 7.3 | 0.79 | 3 |
| 102158 | -0.46 | 0.40 | 0.34 | 13.5 | 114.4 | -118.0 | 10.1 | 151.5 | 9.9 | 0.2 | 0.57 | 2 |
| 102200 | -1.24 | 0.30 | 0.57 | 14.0 | -86.5 | -131.0 | 6.4 | 155.5 | 9.5 | 0.2 | 0.61 | 3 |
| 103095 | -1.35 | 0.28 | 0.55 | 14.0 | -278.0 | -160.0 | -13.4 | 325.3 | 21.8 | 0.2 | 0.90 | 4 |
| 109358 | -0.21 | 0.07 | | 7.5 | 30.8 | -3.3 | 1.5 | 23.1 | 9.4 | 0.1 | 0.07 | 1 |
| 112758 | -0.43 | 0.36 | 0.28 | 12.5 | 75.7 | -34.1 | 16.4 | 73.5 | 9.8 | 0.3 | 0.23 | 2 |
| 114710 | -0.03 | 0.01 | 0.01 | 3.5 | 50.6 | 8.7 | 8.5 | 47.0 | 10.9 | 0.2 | 0.16 | 1 |
| 114762 | -0.71 | 0.33 | | 12.5 | 82.0 | -70.5 | 57.8 | 113.6 | 9.5 | 1.3 | 0.34 | 2 |
| 117176 | -0.11 | 0.08 | 0.04 | 8.1 | -13.7 | -51.7 | -3.8 | 48.0 | 8.6 | 0.0 | 0.20 | 1 |

| HD/BD | [Fe/H] dex | [Mg/Fe] dex | [Eu/Fe] dex | t, Gyr | U, km/s | V, km/s | W, km/s | $V_{pec}$, km/s | Ra, kpc | $Z_{max}$, kpc | e | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 121560 | -0.43 | 0.15 | 0.14 | 5.0 | 29.2 | -20.1 | -3.1 | 21.9 | 8.8 | 0.0 | 0.08 | 1 |
| 122196 | -1.71 | 0.16 | 0.24 | 12.0 | 171.8 | -143.0 | 14.0 | 210.8 | 11.5 | 0.3 | 0.73 | 3 |
| 126053 | -0.35 | 0.14 | 0.14 | 9.0 | -22.4 | -15.2 | -39.3 | 46.7 | 9.3 | 0.5 | 0.11 | 1 |
| 130322 | 0.04 | 0.02 | -0.04 | 1.0 | 9.4 | -26.0 | -11.0 | 16.8 | 8.5 | 0.1 | 0.07 | 1 |
| 132142 | -0.39 | 0.31 | 0.26 | 12.5 | 108.4 | -55.9 | 19.6 | 111.6 | 10.5 | 0.4 | 0.37 | 2 |
| 134987 | 0.25 | 0.00 | -0.17 | 6.0 | 20.5 | -40.2 | 20.8 | 41.7 | 8.5 | 0.3 | 0.14 | 1 |
| 142373 | -0.57 | 0.22 | 0.23 | 8.5 | 41.8 | 10.4 | -68.2 | 72.8 | 11.3 | 1.3 | 0.16 | 1 |
| 144579 | -0.69 | 0.38 | 0.46 | 12.5 | 35.5 | -58.2 | -18.0 | 55.8 | 8.6 | 0.1 | 0.23 | 2 |
| 148816 | -0.78 | 0.41 | 0.30 | 12.0 | -86.5 | -262.0 | -79.2 | 280.4 | 9.7 | 5.4 | 0.89 | 4 |
| 157214 | -0.34 | 0.38 | 0.34 | 12.5 | -26.1 | -80.4 | -63.8 | 97.9 | 8.7 | 1.1 | 0.32 | 2 |
| 168009 | -0.03 | 0.04 | -0.08 | 9.0 | 4.4 | -61.7 | -22.5 | 54.5 | 8.5 | 0.2 | 0.24 | 1 |
| 176377 | -0.27 | 0.07 | | 2.5 | 38.5 | -23.7 | -4.7 | 31.7 | 8.9 | 0.0 | 0.11 | 1 |
| 179957 | -0.01 | 0.05 | 0.03 | 8.0 | 67.2 | -44.0 | 35.5 | 78.4 | 9.4 | 0.7 | 0.23 | 1 |